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Tolerance verification of precision injection moulded Fresnel lenses

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Abstract

Injection Moulding (IM) and Injection Compression Moulding (ICM) are the leading process technologies to enable mass manufacturing of Fresnel lenses. Even though ICM requires a more expensive and complex process, it is proven to lead to higher optical performances in comparison with IM. In this study, tolerancing for ICM and IM addresses the geometrical accuracy and precision of the two manufacturing processes when micro structures of Fresnel lens surfaces are taken into account.

Keywords: Tolerancing, Injection Moulding, Injection Compression Moulding, Fresnel Lenses, Uncertainty, Micro-Metrology

1. Introduction

Polymer optics are optical components with a very broad field of applications, starting from automotive to industrial and private illumination, electronics, and biomedical optical-based equipment or machinery.

Fresnel lenses are specifically developed optics with reduced dimensions and enhanced light gathering properties. The design of these lenses consists in the segmentation of a conventional plano convex lens into a composition of annular and concentric grooves, with a triangular cross-section profile.

The geometry of Fresnel lens surface grooves defines the lens ideal optical properties. For example, f-number, i.e. the ratio between focal length and effective aperture, can be mathematically described by the facet angle of the grooves [1]. In addition, the height of the grooves has a direct impact on the transmission efficiency [2] and the chromatic aberration of the lens [3].

However, not only the geometry affects the optical properties of the lens, the combination of material and manufacturing processes can lead to very different optical functionality. When light is passing through the part, double refraction known as birefringence, can occur in dependence of polymer chains orientations, entanglement and length. The overall chains distribution depends on both polymer rheology and processing conditions, as long as internal stresses in the part. Overall, the optical performances can be measured in terms of light absorption, transmission efficiency and birefringence [4].

In the particular case of automotive lighting applications, the manufacturing processes are bounded to meet the demanding capability and production volumes requirements of the industry. Successful examples of adopted materials are Cyclic

Nomenclature

IM	Injection Moulding
ICM	Injection Compression Moulding
COP	Cyclic Olefin Polymer
PMMA	Poly Methyl Methacrylate
GPS	Geometrical Products Specifications
DPMO	Defects Per Million Opportunity
SL	Specification Limits
WL	Warning Limits
CL	Control Limits

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Olefin Polymer (COP) and Poly Methyl Methacrylate (PMMA), whose high transmission efficiency and low water absorption make these materials functional and long-lasting [5,6].

Injection Moulding (IM) and Injection Compression Moulding (ICM) are popular because of their large scale productivity and reproducibility. The selection of ICM with respect to IM leads to a further improvement of the optical performances by reducing the birefringence through a more homogenous replication of the cavity [7-9].

So far, quality control on manufactured Fresnel lenses consists in functional tests of the optical performances, while geometrical dimensions are tested separately to verify the assembly requirements of the parts.

In this context, precision and accuracy of the replicated Fresnel lens grooves are generally not inspected. The major challenges for this task are represented by multiple interconnected constraints, such as:

- Availability of cost-effective micro- and nano-metrology for the moulding industry.
- Lack of traceable methods for assessing Geometrical Product Specifications (GPS) of micro moulded transparent optical components [10].
- Unspecified process capability for micro moulded features.
- Limited understanding of functional losses, due to inefficient replication of micro structures on overall optical performances.

Therefore, tolerance specifications are typically not defined on moulded Fresnel lens micro structure geometry.

In this study, a metrological solution to assess transparent micro features replication of injection moulded and injection compression moulded Fresnel lenses is proposed, supporting the implementation of tolerance chain verification of ICM and IM micro features.

2. Tolerancing μ-features in optical parts

Tolerance specifications are a fundamental design tool for assessing process and production quality. They enable the control on supply and process chains accuracy (intended as difference between the process average response and the target one) and precision (intended as standard deviation of the process response with respect to its average), in order to ensure the functionality of the desired product.

Standard ISO 10110-1:2006 [11], describes the ISO standards series ISO 10110, which specifies "*the presentation of design and functional requirements for optical elements and systems in technical drawings used for manufacturing and inspection*" and "*the presentation in drawings of the characteristics, especially the tolerances, of optical elements and systems"*.

Nevertheless, the standard series does address explicitly to the case of tolerance verification for Fresnel lenses surface design.

Normally, a dimensional or geometrical tolerance specification, is meant to ensure a functional requirement. When the functional requirements are not measurable directly, the Geometrical Products Specifications (GPS) can be adopted as tolerance verification procedure.

However, when the geometrical features are in the micro dimensional scale, also the tolerance specifications with this method become limited [12]. In fact, considering the cost of tolerance verification with respect to geometrical dimensions [13], GPS 286-1:2010 [14] does not impose a standard tolerance specification table for two-point measurements below 3 mm. In this geometrical scale, both measuring uncertainty and calibration procedures become more expensive to be achieved, considering the higher required accuracy and precision of the metrological chain.

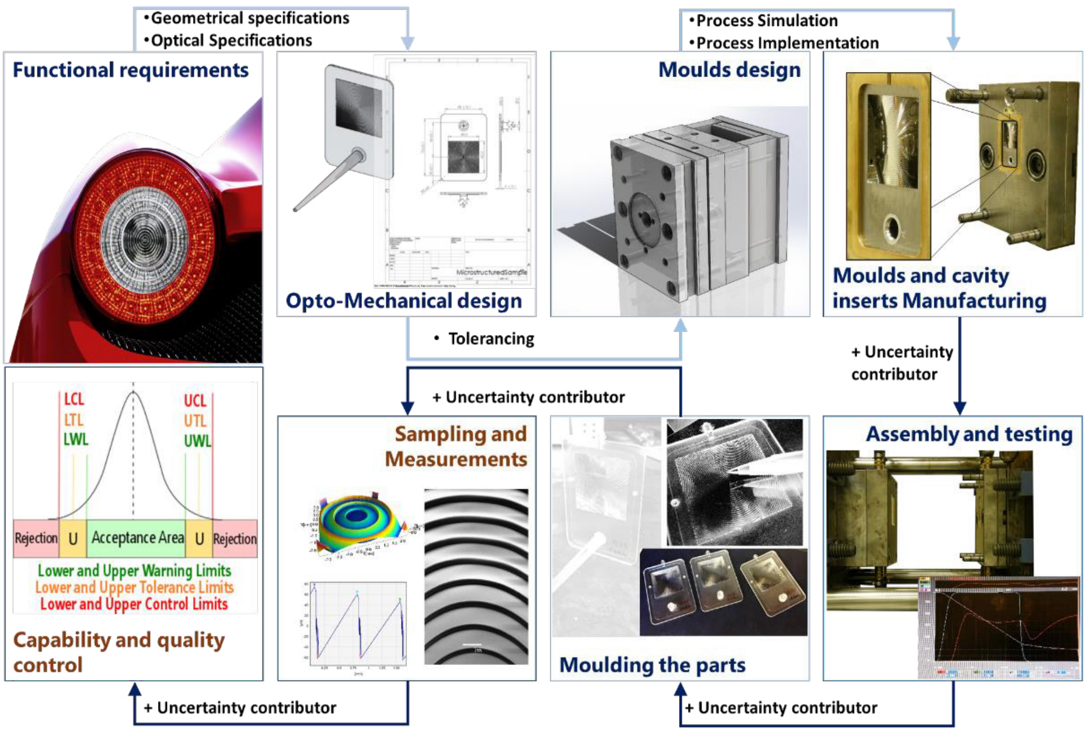

Fig. 1. Moulding based process chain for optical parts.

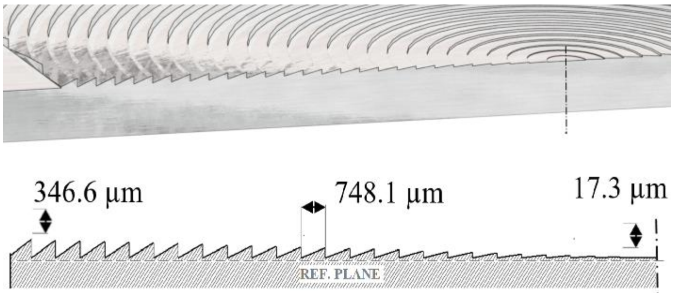

Fig. 2 . Fresnel transparent surface 3D section and profile.

In the case of Fresnel lens surface micro features, a standard correlation between functionality loss and individual features geometry is missing. In addition, both optical standards and geometrical specification do not provide a general guideline for tolerance verification in the case in which the features have micro dimensional scale.

Therefore, tolerances on Fresnel surface features geometry are most commonly not set. To fill this normative gap and help lenses manufactures in defining new quality control procedures, the optical micro features could be measured and subsequently correlated to a functional performance. A metrological solution is proposed in the next paragraph.

Fig 1 depicts the typical manufacturing process chain of Fresnel lenses. Step height of a Fresnel surface micro groove will be measured considering the already mentioned influence on optical performance. In this way, it is possible to address production capability and process quality on the step height replication after moulding. A further understanding of uncertainty contributors occurring along the process chain becomes economically relevant in the sense that less parts are non-conformal to the specification.

3. A metrological solution for a transparent Fresnel surface

The definition of the measurands on the lens surface geometry is inspired to a circular groove standard, defined in ISO 25178-70:2014 [15]. The studied Fresnel surface consists of an automotive derivate design generated on a rectangular lens with overall component dimensions of 85 mm x 60 mm x 2 mm. The Fresnel structured area covers a square region with dimensions of 40.2 mm x 40.2 mm.

The micro structures, consisting of concentric grooves with a constant nominal pitch of 748.1 µm, have a variable step height, ranging from 17.3 µm, in the lens centre, to 346.6 µm in the external side. A 3D section and a section view of the lens centre are shown in Fig. 2. The material used for the experimentation is Cyclo Olefin Polymer (COP) available on the market as ZEONEX® E48R, from ZEON®, Tokyo, Japan.

The adopted metrological solution consists in the utilization of optical microscopy, as shown in Fig. 3, specifically of a laser scanning confocal instrument (Lext OLS-4100 by Olympus®, Tokyo, Japan). The microscope mounts a blue 410 nm laser source and the 20x objective. The objective has a numerical aperture of 0.6 and a working distance of 1 mm.

The smallest step height of 17.3 µm nominal dimension is measured as point distance between the maximum and the minimum point data height (Peak-to-Valley), as shown in Figure 3 (b) and (c).

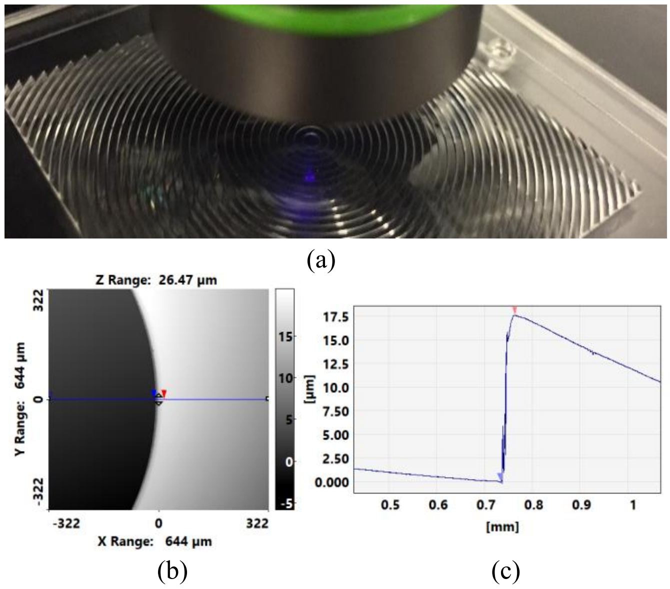

Fig. 3 Measuring Fresnel surface with Laser Scanning Confocal Microscopy (a), image processing (b) and profile extraction (c).

4. Definition of tolerance specification for Fresnel surface micro steps

To address the step height tolerance of Fresnel micro grooves, a methodology is proposed taking into account the equivalent aspheric curve on which the Fresnel lens surface can be projected. The aspheric equation, as shown in Eq. 1, plots the z height value on the optical axis against their radial coordinates.

The equation contains n higher order even polynomials, characterised by the parameters α_{2i}, assuming the axial-symmetricity of the equation. The equation is approximated to the first term and fitted against the incremental sum of step of the Fresnel profile with least square method. In the equation, c is the curvature of the osculating circle near the lens centre ($r = 0$). The conic constant, κ, indicates the eccentricity of the asphere.

$$z(r) = \frac{c\, r^2}{1 + \sqrt{1 - (1+\kappa)\, c^2\, r^2}} + \sum_{i=1}^{n} \alpha_{2i} r^{2i} \tag{1}$$

In Figure 4, the resulting aspheric function is plotted. The curvature c is of 0.025 1/mm and the conic constant is equal to -1.26 indicating a hyperbolic conic section.

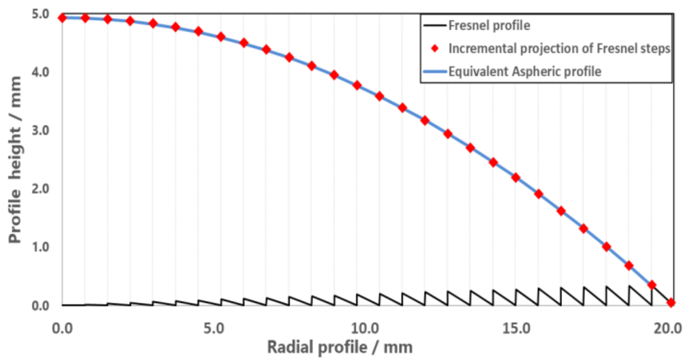

Fig. 4 Fresnel profile and equivalent aspheric envelope.

Table 1. Tolerance specification on the step height of Fresnel lens profile.

Fresnel lens step height /µm	$\partial z/\partial r$	Specification on lens diameter / µm	Tolerance on step height / µm
17.3	0.0186	±125	±1
60.9	0.0737	±125	±5
118.1	0.1470	±125	±9
173.6	0.2196	±125	±14
226.7	0.2914	±125	±18
277.1	0.3619	±125	±23
324.3	0.4311	±125	±27
346.6	0.4792	±125	±30

Because the diameter of the lens affects all the optical properties, lens manufacturers provide specifications for this value. For the equivalent aspheric lens, the tolerance on a diameter of 40.2 mm is ± 0.125 mm. By calculating the numerical derivate of the aspheric function with respect to its radial coordinate, it is possible to link the maximum radial deviation allowed to maximum step height deviation allowed, defining the tolerance specification. The method is represented in Eq. 2.

$$\Delta z_{max} = \frac{\partial z}{\partial r}\,\Delta r_{max} \tag{2}$$

In Table 1, specifications for the different step heights are calculated and presented.

5. Uncertainty budget

The estimation of expanded uncertainty is inspired to ISO 15530-3:2015 [16]. The individual uncertainty contributors are contained in Eq. 3. For the evaluation, ten replicated measurements on the calibrated artifact (u_b, u_p), one measurement on ten different process replicates (u_{wf}) and ten measurments on the same lens sample (u_{wt}, u_{wp}) have been considered.

$$U = k\, \times \sqrt{{u_{cal}}^2 + {u_b}^2 + {u_p}^2 + {u_{wt}}^2 + {u_{wp}}^2 + u_{wform}} \tag{3}$$

The first contributor u_{cal} addresses to the uncertainty of the calibrated reference sample. The calibrated reference is constructed by aligning two steel gauge blocks, grade two, of length 1019.70 µm and 1005.25 µm, which generate a step height of 14.45 µm. The uncertainty associated to this value is the width tolerance of the gauge block according to the ISO 3650:1998 [17], scaled with a rectangular distribution.

The standard uncertainty associated to systematic effects during measurements u_b, addresses to thermal effects only and is calculated with Eq. 4.

$$u_b = l\, \times \sqrt{(\Delta T \times u_\alpha)^2 + (\alpha\, \times u_{\Delta T})^2} \tag{4}$$

Where ΔT = 0.25 C is the laboratory average temperature minus the reference temperature. The uncertainty of the thermal expansion coefficient, u_α has a value of 10^{-7} C^{-1} while the coefficient of thermal expansion, α of the calibrated reference is 1.13 x 10^{-5} C^{-1}.

Table 2. Uncertainty budget

Uncertainty contribution	Values	Description
k	2	Coverage factor
u_{cal}	0.26 µm	Standard uncertainty associated to the calibrated reference
u_b	0.00 µm	Standard uncertainty due to thermal effects while measuring the calibrated reference
u_p	0.03 µm	Standard uncertainty of the measurement procedure on the calibrated sample
u_{wt}	0.01 µm	Standard uncertainty due to thermal effects while measuring the lens sample
u_{wp}	0.13 µm	Standard uncertainty of the measurement procedure on the lens sample
u_{wf}	0.17 µm	Standard uncertainty associated with the form deviations in the lens samples
U	0.67 µm	Expanded Uncertainty

The temperature standard uncertainty is considered cyclical and consequently calculated as reported in Eq. 5.

$$u_{\Delta T} = \frac{\Delta T}{2\times\sqrt{2}} \tag{5}$$

Furthermore, the standard uncertainty of measurement procedure u_p, is calculated as standard deviation of the repeated measures on the calibration sample. The standard uncertainty associated to the measured lens is divided in three other contributors. The first one, u_{wt}, takes into account the systematic components due to thermal effects while measuring the sample. Eq. 4 is adopted considering in this case: ΔT = 0.50 C, u_α =1.4 x 10^{-6} C^{-1} and the coefficient of thermal expansion of the COP material, α, is equal to 6.25 x 10^{-5} C^{-1}, as provided by the material manufacturer. The second uncertainty contributor u_{wp}, is associated to the measuring procedure of the sample and includes the possible different interaction between microscope and sample with respect to the calibrated one. It is calculated as standard deviation of the ten repeated measurements on the same lens sample. The last contributor, u_{wf}, takes into consideration the form deviation due to manufacturing process variability. It is calculated as rectangular distribution of the range of measurements on ten different lenses moulded with the same process conditions. The calculation is shown in Eq. 6.

$$u_{wf} = \frac{l_{max} - l_{min}}{3\times\sqrt{2}} \tag{6}$$

For both IM and ICM the contributor is calculated and results equal to 0.17 µm. The final expanded uncertainty is 0.67 µm considering a coverage factor k, equal to 2, to have approximately 95% of statistical confidence. All the contributors are presented in Table 2.

6. IM and ICM of Fresnel lens micro features

IM and ICM were performed on a V70-180 injection compression moulding machine by NegriBossi®, Milano, Italy. The IM and ICM experiments are carried out in industrially relevant working conditions. To provide a process statistical control, the experiments have been carried out in the same working day, by the same operator during a single shift.

Table 3: IM and ICM process conditions.

Process parameter	Value	Moulding process
Melt Temperature	*280 °C*	IM, ICM
Mould Temperature	*105 °C*	IM, ICM
Injection Velocity	*40 mm/s*	IM, ICM
Compression Gap	1.0 mm	ICM
Switch over point	13 mm	IM, ICM
Packing Pressure	450 bar	IM, ICM
Cooling Time	22 s	IM, ICM

The sampling procedure starts after an initial machine warm-up. It consists of twenty unmeasured shots that are discarded. Afterwards, ten consecutive samples are measured in a controlled environment, following the metrological strategy explained in paragraph 3. The injection parameters shown in Table 3 i.e. melt temperature, injection velocity, switch over point, packing pressure, cooling time and mould temperature, are the same for both IM and ICM. The parameters selection is the outcome of a previous optimisation study following the design of experiments technique. In ICM, a compression phase is introduced before the beginning of packing phase with a Compression Gap of 1 mm.

Compression is allowed by a movable brass insert on the movable mould plate. The cavity insert on the fixed side is instead tooled with the Fresnel surface. It is manufactured with an electroforming and diamond machining-based process chain in Nickel material, which ensure the optical requirements in terms of precision and accuracy [18].

6.1 Production capability

Production capability is estimated using *Cp* and *Cpk* (Eq. 7,8) process capability indexes, in state of statistical process control.

$$C_p = \frac{USL-LSL}{6\sigma} \tag{7}$$

$$C_{pk} = \min\left(\frac{USL-\mu}{3\,\sigma}; \frac{\mu-LSL}{3\,\sigma}\right) \tag{8}$$

The lower and upper specifications levels (*LSL*, *ULS*) are defined with the tolerance specification of Table 1. In this case, a symmetric tolerance zone of ±1 µm on the nominal value of 17.3 µm is defined. The expanded uncertainty associated to the measurements has a dimension comparable to the tolerance. The acceptance level, which is the ratio between the tolerance zone and the expanded uncertainty is 67 %.

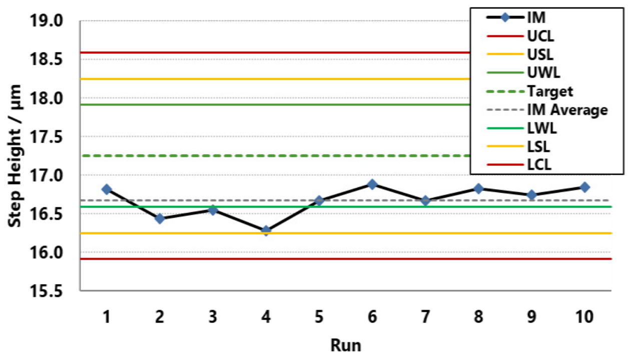

Fig. 5 IM Process control Chart.

Table 4. IM and ICM replication conditions

Result	IM	ICM
Average / µm	*16.7*	*16.9*
Absolute deviation from target / µm	*0.6*	*0.4*
Replication fidelity %	*96.7*	*98.0*
St. Deviation / µm	*0.2*	*0.2*
Cp	*1.7*	*1.7*
Cpk	*0.7*	*1.0*
DPMO	15 659	1089

Lower and upper Warning and control limits (*LWL*, *UWL*) (*LCL*, *UCL*) are calculated summing and subtracting respectively the half of the expanded uncertainty from the specification levels. In Eq. 7 and 8, σ is the sample standard deviation while μ is the average of the different process treatments. The capability indexes are calculated without considering expanded uncertainty. For this reasons process charts are shown in Fig 5 and 6 to verify the location of single treatments. Normality assumption cannot be rejected as Anderson-Darling test shows not significance in p-values for both the samples.

7. Results

The average and standard deviation of the results of the IM and ICM process are reported in Table 4. Replication fidelity in percentage is also reported as ratio between average and nominal value of 17.3µm. The process precision can be considered equal to the process standard deviation, which is equal for both IM and ICM to 0.2 µm.

Process accuracy, is quantified as the deviation of the average result from the target nominal dimension. ICM is more accurate than IM, considering a bias from target value of 0.4 µm against 0.6 µm of the IM results. This confirms that Compression leads to an improvement in the replication of the Fresnel micro surface. The charts in Fig. 5 and Fig. 6 show that the processes are biased from the nominal target, but no outliers or trends are encountered during the production. Treatments number 2, 3 and 4 for IM and treatment number 3 in ICM require further inspection before acceptance, because they undergo the warning limits due to measurements uncertainty. Analysing the capability indexes, both the processes are precise (*Cp*>1). However, process accuracy, indicated by a *Cpk,* equal to 0.7 for IM and 1.0 for ICM, can be improved. This is visualized in the process distribution chart in Fig. 7 and Fig.8.

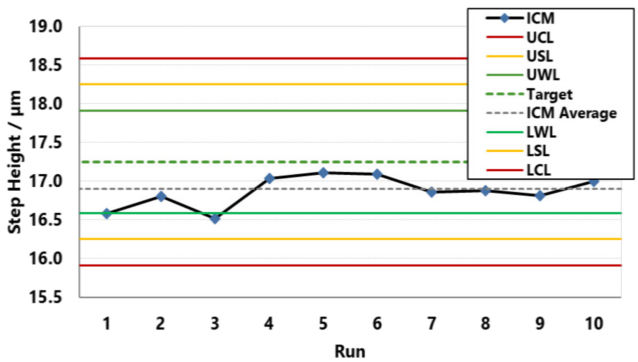

Fig. 6 ICM Process control Chart.

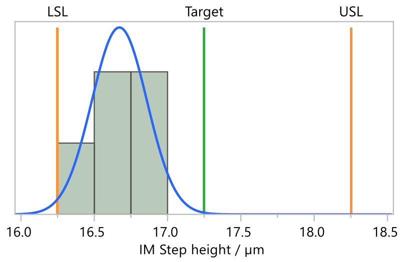

Fig. 7 IM Process distribution.

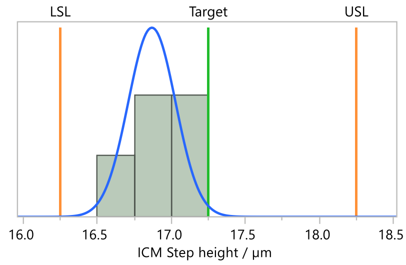

Fig. 8 ICM Process distribution.

To improve the accuracy, it is necessary to first investigate the effective geometry of the mould, and then to compensate for the replication loss by correcting (i.e. increasing in this case) the profile height in the insert design. When this is not possible, the choice of ICM can lead to an economical saving due to the lower DPMO (Defects Per Million Opportunity). As shown in Table 4, an overall probability of producing defect part, is 15 times larger for IM than ICM, 15659 against 1089.

8. Conclusions

In this paper, a methodology for the inspection of Fresnel surface micro structures and the determination of the process capability for their manufacture is proposed. The conclusion can be summarized as follows.

- First of all, by using a laser scanning confocal microscope, calibrated with gauge blocks, a cost-effective micro metrology solution is proposed and validated.
- A numerical methodology is proposed to define tolerance specification on Fresnel surface micro features, linking maximum radial variation with step height maximum deviation.
- Secondly, a detailed evaluation of uncertainty contributors during measurement provides the estimation of the expanded uncertainty ($U = 0.67$ µm) for a nominal value of 17.3 µm step height of the Fresnel structured surface profile.
- A preliminary process capability analysis proved that both IM and ICM are precise processes ($Cp > 1$), but ICM ($Cpk = 1.0$) results more performing in terms of process accuracy than IM ($Cpk = 0.7$).

The present study provides the knowledge for a future work for the establishment of the correlation between micro structures replication and the overall Fresnel lens optical performance.

Acknowledgements

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